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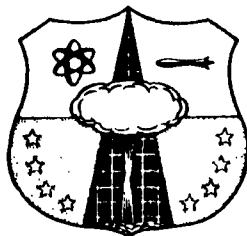
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# EXPERIMENTAL TESTS FOR THE ACCELERATION
# OF TRAPPED PARTICLES

by

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TECHNICAL DOCUMENTARY REPORT NO. AFSWC-TDR-62-133

January 1963

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New Mexico

MAR 1 1963

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Project No. 7811, Task No. 781107

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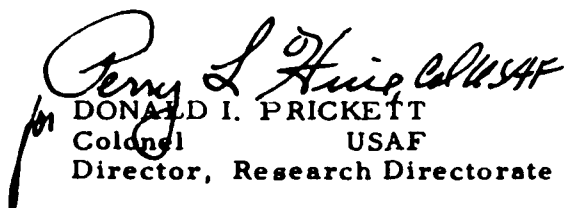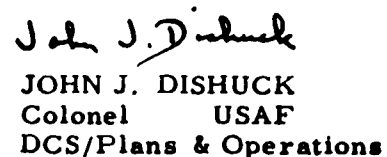
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## ABSTRACT

Mechanisms which could result in the acceleration of charged particles within the magnetosphere are discussed in terms of the responses expected from experimental instruments as they pass through acceleration regions. A series of experimental tests is outlined which can determine if acceleration of trapped particles is important. The mechanisms discussed include Fermi acceleration, which can accelerate protons to tens or hundreds of kilovolts and can increase the energy of trapped electrons several hundred-fold before they are lost in the dense atmosphere. A change in the intensity of the solar wind or in the strength of a ring current can change the energy of trapped particles by the betatron mechanism. Electrons can be accelerated to kilovolt energies by the setting up of plasma oscillations, by acceleration within moving clouds or by intrusions of solar plasma. Finally, particles may be accelerated to energies of 10 kilovolts or more in the vicinity of neutral lines.

## PUBLICATION REVIEW

This report has been reviewed and is approved.

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# CONTENTS

## 1. INTRODUCTION,

A number of mechanisms have been proposed which could result in the acceleration of charged particles trapped within the magnetosphere. Some confusion can result, however, in the interpretation of experimental measurements in terms of these mechanisms. In this work, the acceleration mechanisms will be reviewed and the responses expected from detectors as they pass through regions in which acceleration is taking place will be described. A set of measurements which can determine the importance of each acceleration mechanism will also be proposed.

To examine the relative importance of acceleration as compared to other mechanisms which could produce energetic trapped particles, several mechanisms which supplement local acceleration are described briefly in section 2. In section 3, mechanisms which can accelerate trapped particles in the boundary region (the region separating the magnetosphere from the interplanetary plasma) are described, and experimental tests are proposed which can determine if each of these mechanisms is important. Mechanisms which can accelerate trapped particles throughout the magnetosphere are similarly treated in section 4. It is pointed out in section 5 that several additional measurements are required concerning the structure of the magnetosphere and the lifetimes of trapped particles to properly interpret the results of measurements which determine if a given acceleration mechanism is operating. Finally, in section 6, the fluxes of trapped particles which have been observed are compared with the fluxes that would be produced by local acceleration, and those acceleration mechanisms which are most likely to be important in each region of the magnetosphere are selected.

## 2. THE IMPORTANCE OF ACCELERATION MECHANISMS TO THE PROBLEMS OF TRAPPED RADIATION.

Present theories concerning the formation of the Van Allen belts and variations taking place in them are limited by lack of a firm understanding of the mechanisms which transfer energy from the sun or from interplanetary space to the magnetosphere. The mechanisms which will be emphasized in the present work involve the local acceleration of charged particles which are already present within the magnetosphere. To illustrate the significance of local acceleration mechanisms to the entire trapped radiation problem, other mechanisms will first be reviewed briefly.

Neutron albedo, High-energy galactic cosmic rays and high-energy solar particles can pass through the magnetosphere and strike the dense atmosphere surrounding the earth. These particles will induce nuclear reactions when they strike air atoms and will produce a number of secondary products. Those products which are charged will mirror at low altitudes and lose energy quite rapidly, so they will not contribute significantly to the flux of trapped particles. Some of the neutrons which are produced, however, will escape from the atmosphere and decay while passing through the magnetosphere. The products of these neutrons can therefore become trapped so that their mirror points are well above the dense atmosphere. This mechanism is generally referred to as albedo neutron injection. It has been discussed in some detail by Hess (1959) and by Lenchek and Singer (1962). The neutron albedo mechanism, therefore, couples energy from high-energy particles in interplanetary space to the trapped-particle regions via the production of new charged particles.

Direct injection. One obvious way to couple energy from interplanetary space to the trapped particle regions is to inject high-energy particles directly into the magnetosphere. Two types of direct injection will be of interest here. First we can consider a steady state condition in which a stable magnetosphere is surrounded by a uniform plasma containing energetic particles. In this condition, particles will diffuse across the boundary separating the magnetosphere from interplanetary space, and an equilibrium will eventually be reached. Assuming a magnetic field is present in the interplanetary plasma and that energetic particles are constrained to move along these field lines, then the ratio of the number density of energetic particles outside the magnetosphere to that inside will equal the ratio of field strengths outside to inside at equilibrium. It has been observed experimentally that the magnitude of the magnetic field does not change a great deal as the interface is crossed (Cahill 1962), so the number density of particles just inside the magnetosphere due to diffusion across the interface will approach the number density outside.

A higher density could be reached inside if special forms of instabilities exist on the interface. For example, it is conceivable that a tongue-shaped intrusion of solar plasma could penetrate into the magnetosphere. If such an intrusion formed, it would do so rather quickly. The conductivity on the boundary of the intrusion would be high, so there would be little diffusion

across this boundary during the formation stage. Such an intrusion would be unstable and break up to leave one or more clouds of solar particles within the magnetosphere. The earth's magnetic field would then slowly diffuse into these clouds, and the particles within them would become trapped. This mechanism could therefore inject a high density of particles into the magnetosphere. There is, however, no experimental evidence which suggests that such large-scale intrusions penetrate to the heart of either Van Allen belt. Therefore, it appears quite unlikely that they could be numerous enough to produce the large changes observed in the outer Van Allen belt during geomagnetic storms.

3. ACCELERATION IN THE BOUNDARY REGION.

In the preceding section, two mechanisms of energy transfer were described. First, it is possible to produce new particles which have a large amount of energy when they are formed; second, it is possible to directly inject energetic particles into the magnetosphere. The third type of energy transfer that can be imagined involves the acceleration of low-energy particles which are already present within the magnetosphere.

Acceleration mechanisms can be divided into two classes. Some mechanisms are important only in the boundary region where the solar plasma comes directly into contact with low-energy particles in the magnetosphere. The second group of mechanisms that will be discussed can accelerate particles anywhere within the magnetosphere.

Fermi acceleration in the boundary region. Fermi (1949, 1954) described a mechanism by which the energy of moving magnetic fields can be transferred to individual charged particles. The basic form of this mechanism involves a hydromagnetic wave moving along a field line. If a charged particle approaches the wave from the front it may, depending on its pitch angle, be reflected from the moving wave. In the nonrelativistic limit, the particle's velocity will increase by twice the wave velocity as a result of this reflection. Similarly, a particle which overtakes the wave can be reflected, but this particle will be decelerated. The net result of a large number of random interactions is a slow transfer of energy from the wave to the individual charged particles. Though a wave has been used in this illustration, Fermi acceleration can be produced by any moving magnetic field, such as the field that could be carried

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within a plasma cloud.

The Fermi mechanism may be important in both the regions previously mentioned, i.e., in the boundary region and throughout the magnetosphere. In the boundary region, clouds or waves in the interface itself will move with velocities which roughly equal the solar-wind streaming velocity of several hundred kilometers per second. The velocity of a charged particle is changed by about the velocity of the moving disturbance in each interaction, so the energy of electrons will be changed by 1 or a few electron volts at each interaction and few electrons will be accelerated to energies exceeding tens of electron volts. Protons, however, will gain or lose 1 to several kilovolts at each interaction, so it appears possible to produce protons with energies of tens or even hundreds of kilovolts in a time which is short compared to the duration of a magnetic storm. A more detailed description of the energy distribution to be expected from this type of Fermi acceleration has been given by Parker (1958).

The experimental measurements that are required to determine if the Fermi mechanism is important in the boundary region can now be described. This mechanism results in the acceleration of protons in the background plasma to energies as high as tens or hundreds of kilovolts. However, a belt of protons in this energy range does not necessarily imply that they were produced by Fermi acceleration. It is therefore necessary to determine if a region exists in which Fermi acceleration is inevitable. The actual parameters that must be measured in the boundary region are:

a. The extent of the turbulent region (or depth of penetration of intrusions).

b. The size of the turbulent structures or clouds.

c. Magnetic field strength as a function of position within the turbulent structures.

d. Velocity (speed and direction) of the turbulent structures or of waves in the interface itself.

e. Energy spectrum of protons in the background plasma.

Once these measurements have been made, the importance of this form of the Fermi mechanism can be determined from an analysis similar to that given

by Parker (1958). Since this mechanism may be important in only a small part of the boundary region, measurements are required at several angles from the earth-sun line.

A set of instruments which can make the required measurements will now be described. A low-energy proton spectrometer will determine the proton-energy spectrum and will detect the presence of turbulence or clouds of solar particles. The energy range of importance is from 10 ev to 50 kev. Detection of protons with energies below 100 ev will require a measurement of the vehicle potential to within a few volts (see appendix).

A magnetometer which takes readings at intervals of about 0.1 second will provide the needed magnetic field measurements. These closely spaced readings are required, since, if intrusions are formed, they will have thin boundaries (1 ion cyclotron radius thick) and they may have speeds up to the streaming velocity of the solar plasma. This surface could therefore pass a detector in $\frac{1}{\omega_c}$ seconds where $\omega_c$ is the ion cyclotron angular frequency. This time interval is 0.1 second if the field strength at the surface of an intrusion is 100 gammas. The requirement for a rapid repetition rate is also evident from measurements which have been made in the boundary region in which an appreciable change in the magnetic field was detected in a time interval of 1 second (Sonett, 1960).

The most straightforward way of measuring the size, speed, and direction of motion of clouds or turbulent structures and the direction of propagation and dispersion relations of hydromagnetic waves is to use two or more detectors separated by distances of a few hundred kilometers. The information required from the second detector is the transit time of the turbulent structure or hydromagnetic wave, so this detector need only be able to identify the presence of a specific structure. This will probably require only a magnetic field measurement. Two detectors can determine one component of the velocity and can measure the length of one chord of a cloud, while four detectors can give all three components of the velocity.

Acceleration by electric fields at plasma boundaries. Ferraro (1952) showed that when a proton-electron pair is stopped by a magnetic field in free space, the proton will transfer nearly all its energy to the electron by the time the forward motion of the ion pair has stopped. The energy will be transferred

back to the proton as the ion pair is accelerated back out of the magnetic field. This energy transfer depends on an electric field set up as the ion pair enters the magnetic field. The proton will tend to penetrate deeper into the field than the electron, so the electron will be dragged along and accelerated by the electric field set up because of charge separation. If a background plasma is present, this field will be much smaller than it would be in free space, and the proton's energy will be distributed among many electrons in the background plasma rather than being transferred to the one incident electron. Therefore, depending on the relative densities of the stationary and streaming plasmas, electrons may temporarily be accelerated up to the energy of protons of the solar wind in some regions of space, and in other regions no such acceleration will be noted. Since this is a reversible acceleration mechanism, i.e., the accelerated electrons will not be trapped but will transfer energy back to the protons after they are reflected, it is important to distinguish between these electrons and electrons accelerated by other mechanisms.

Energy can also be transferred from protons to electrons by the excitation of plasma oscillations. Noerdlinger (1961) reviewed the models which have been proposed, and showed that in the absence of a transverse magnetic field it is unlikely that large amplitude oscillations would be excited in the interaction of a plasma similar to that streaming from the sun with a stationary plasma similar to that surrounding the earth. It is possible, however, that plasma oscillations are important in the case of interest here, because of the presence of the earth's magnetic field.

Acceleration in gas clouds. Veksler (1958) has described a mechanism by which the kinetic energy of a gas cloud (which is initially carried mainly by the protons) can be transferred to the electrons as the cloud moves in a magnetic field. In this mechanism, the motion of the cloud across a magnetic field causes a current to be set up within the cloud. The energy carried by this current is then dissipated as heat within the cloud, and a drag force is produced which retards the motion of the cloud. In this manner, an appreciable fraction of the kinetic energy of the cloud can be transferred to electrons within the cloud. Since solar-wind protons have energies on the order of a kilovolt, this provides a mechanism for the production of kilovolt electrons in the boundary region.

Experimental tests are required to determine which, if any, of the mechanisms described to produce kilovolt energy electrons are important. Acceleration of electrons by electric fields set up at plasma boundaries and in gas clouds can be studied by measuring the electron energy spectrum as a function of position within the boundary region. Because of the thin interfaces involved, measurements must be made at intervals of one or a few tenths of a second, as discussed previously in connection with magnetic field measurements. The electron energy range of interest is from 10 ev to 10 kev, and the vehicle potential again must be measured to obtain accurate information on particles with energies of less than 100 ev. To distinguish between the various mechanisms, some angular information is also required. The reversible acceleration mechanism will only be important at interfaces between a streaming plasma and a magnetic field, and the electrons will have their maximum energies when they are moving parallel to the interface. Acceleration in clouds will be important in regions in which clouds are moving across field lines. Plasma oscillations can be measured with a detector which is sensitive to oscillations near the plasma frequency.

This completes the group of mechanisms which can accelerate ambient particles in the boundary region. The energy ranges which were seen to be most important are 10 ev to 10 kev for electrons and 1 kev to 1 Mev for protons.

## 4. ACCELERATION THROUGHOUT THE MAGNETOSPHERE.

The energy sources which are available throughout the magnetosphere are solar photons, hydromagnetic waves, and electromagnetic radiation. Solar photons are an important energy source in the atmosphere but, because of the conservation of energy and momentum, a free electron cannot absorb all the energy of an incident photon. The maximum energy that can be transferred from a photon with energy $h\nu$ to a free electron is (Evans, p. 676, 1955)

$$E = \frac{h\nu}{1 + (mc^2/h\nu)}$$

where m is the electron mass. For a 100-ev photon, this energy is 0.04 electron volt. Energy transfer to atomic electrons is more efficient, but about $10^{-5}$ g $\cdot$ cm$^{-2}$ of hydrogen is required to reduce the intensity of a

100-ev photon beam to $1/e$ of its initial value (Henke, White, and Lundberg, 1957). About 1 erg $\cdot$ cm$^{-2}$ sec$^{-1}$ of energy reaches the earth from photons with energies between 75 ev and 200 ev (Hinteregger, 1961). Therefore, even in a region in which the hydrogen density is $10^3$ cm$^{-3}$, electrons in this energy range are produced at the rate of only $10^{-6}$ cm$^{-3} \cdot$ day$^{-1}$, so extreme ultraviolet radiation does not appear to represent an important source of energy for the production of charged particles with energies above 100 electron volts.

Most mechanisms which can take place throughout the magnetosphere transfer energy through the formation of hydromagnetic waves in the boundary region. These waves can then carry energy into the magnetosphere and can transfer some of this energy to trapped particles. Since hydromagnetic wave mechanisms involve two energy transfer steps (the formation of waves and the interaction between waves and trapped particles), they are rather inefficient. However, the solar wind is such a large energy source (assuming a density of ten 500-ev protons per cm$^3$, the solar wind can supply the maximum energy that can be trapped in the radiation belts within a half hour) that even very inefficient mechanisms using this energy can be important.

To discuss the acceleration of trapped particles caused by interactions with hydromagnetic waves, it will be necessary to recall something of the particles' motions. Trapped particles execute three basic types of motion: a spiraling around field lines, a bouncing along field lines from one mirror point in the northern hemisphere to one in the southern hemisphere, and a slow drift around the earth. Each of these motions is associated with an adiabatic invariant (Northrop and Teller, 1960). The first invariant is the magnetic moment

$$\mu = \frac{P_\perp^2}{2m_o B} = \frac{E}{B_m} + \frac{E^2}{2B_m m_o c^2}$$

where $P_\perp$ is the component of the particle's momentum perpendicular to the field, $m_o$ is the rest mass, B is the field strength, $B_m$ is the mirror point field strength, and E is the kinetic energy. The magnetic moment of a particle moving in a disturbed field is conserved if the time scale for the field perturbation is much longer than the particle's cyclotron period. Therefore,

any interaction which is slow compared to the cyclotron period and which alters the mirror point of a particle must also alter its energy.

The second or longitudinal invariant can be written

$$I = \int_{B_m}^{B_m^*} \frac{v_{||}}{v} \, ds$$

where $v_{||}$ is the component of the particle's velocity along a field line, $v$ is the total velocity, ds is an element of length along the field line, and the integral is taken from one mirror point to the other. This quantity is conserved if field perturbations are slow compared to the bounce period of the trapped particle.

The third or flux invariant states that the surface traced out by the guiding center of a particle will remain fixed if the perturbation takes place much more slowly than the drift period.

Fermi acceleration from small amplitude hydromagnetic waves. Hydromagnetic waves can be propagated through the magnetosphere with frequencies up to the local ion cyclotron frequency, so there is no assurance that any of the adiabatic invariants will be conserved for protons in the magnetosphere. However, to date there are no observations of hydromagnetic disturbances with frequencies higher than a few cps. If a cutoff near 1 cps exists, then the magnetic moment of protons with energies below a critical value would be conserved (Dragt, 1961). This critical energy is presented in table 1 for a variety of cutoff frequencies and for particles mirroring at various latitudes in a dipole approximation to the earth's field. It can be seen that the critical energy depends very sensitively on the cutoff frequency and mirror point latitude if this latitude is less than about $30^\circ$. It is equally sensitive to errors in the hydromagnetic wave velocity, which was taken from Dessler, Francis and Parker (1960). A reasonable set of values to use could be based on the assumption that hydromagnetic waves extend up to the local proton cyclotron frequency beyond 5 to 8 earth radii, and that below this level a cutoff at 1 to 5 cps exists.

Because of their higher cyclotron frequencies, electrons are less susceptible than protons to scattering by hydromagnetic waves. Table 1 shows that the critical energy below which the magnetic moment is conserved is much higher for electrons than for protons at high altitudes. The second adiabatic invariant will not be conserved for electrons since bounce frequencies are never higher than a few cps.

Any mechanism that changes the mirror point of a charged particle without changing its magnetic moment will also change the particle's energy according to the formula presented in the discussion of adiabatic invariants. A particle whose mirror point moves down a field line will be accelerated until it strikes the dense atmosphere surrounding the earth. Since the field strength high above the earth is only a few tens of gammas and the field strength near the earth's surface is in the tens of thousands of gammas, acceleration by as much as a factor of 1,000 is possible.

When a hydromagnetic wave passes the mirror point of a charged particle, the field will initially become compressed, and the mirror point will move up the field line. As the wave passes, the mirror point will return to its initial position. A hydromagnetic wave, then, causes the mirror point of a charged particle to oscillate up and down along a field line. The trapped particles will therefore be reflected from moving magnetic disturbances, and the result of a large number of interactions will be a transfer of energy to the charged particles. This process has been discussed in some detail by Parker (1961a). He showed that with a given initial distribution of particles, this mechanism will result in a net loss of energy from the trapping region; some particles will be accelerated, but enough will either be decelerated or lost so that there is a net energy loss. it is, however, possible for this type of acceleration to produce an increase in the count rates of experimental instruments. For example, assume a group of kilovolt particles is produced so that they mirror in a 30 γ field. These particles would, of course, not be seen by a detector with a 30-kilovolt threshold. As a result of interactions with hydromagnetic waves, some of these particles will move down the field lines, and in cases in which the magnetic moment is conserved, the energy of those whose mirror points reach a field strength of 1,000 γ will have energies of more than 30 kilovolts, so they could be seen by the detector.

Table 1

CRITICAL ENERGIES FOR CONSERVATION
OF THE MAGNETIC MOMENT

| L (earth radii) | 2 | 3 | 4 | 5 | 6 | 8 | 10 |
|---|---|---|---|---|---|---|---|
| Electrons $v_{max}$ = 1 cps; $\lambda > 30°$ | 5(8) | 5(7) | 1(7) | 3(6) | 8(5) | 6(4) | 8(3) |
| Protons $v_{max}$ = 1 cps; $\lambda > 30°$ | 1.5(8) | 1.5(6) | 8(4) | 7(3) | | | |
| Electrons $v_{max}$ = 5 cps; $\lambda > 30°$ | 1(8) | 1(7) | 2(6) | 4(5) | 8(4) | 3(3) | 3(2) |
| Protons $v_{max}$ = 5 cps; $\lambda > 30°$ | 7(6) | 8(4) | 3(3) | 3(2) | | | |
| $v_p$ (cps) | 59 | 18 | 7.4 | 3.9 | 2.2 | .92 | .47 |
| Electrons $v_{max}$ = $v_p$; $\lambda > 30°$ | 1(7) | 2(6) | 1(6) | 6(5) | 3(5) | 8(4) | 3(4) |
| Protons $v_{max}$ = $v_p$; $\lambda > 30°$ | 5(4) | 5(3) | 1.5(3) | 4(2) | | | |
| Electrons $v_{max}$ = 1 cps; $\lambda$ = 20° | 9(8) | 9(7) | 2(7) | 5(6) | 1.5(6) | 1.5(5) | 2(4) |
| Protons $v_{max}$ = 1 cps; $\lambda$ = 20° | 3(8) | 4(6) | 2(5) | 2(4) | | | |
| Electrons $v_{max}$ = 1 cps; $\lambda$ = 10° | 1.5(9) | 1.5(8) | 3(7) | 9(6) | 3(6) | 4(5) | 6(4) |
| Protons $v_{max}$ = 1 cps; $\lambda$ = 10° | 9(8) | 1.5(7) | 6(5) | 5(4) | | | |

An increase in flux caused by a breakdown of the longitudinal invariant, therefore, does not require a mechanism which produces a net energy increase, but only requires the injection or production of a large number of moderate-energy particles.

Fermi acceleration from large amplitude waves. The changes that take place as a wave propagates down a dipole field line which crosses the equator at 10 earth radii is shown in figure 1. At a, the wave is peaked, and particles which are located within the shaded region and which mirror at a field strength smaller than that at the peak of the wave will be trapped between the moving wave and the stationary field of the earth. These particles will be accelerated each time they are reflected from the wave, and their mirror points will be lowered rapidly. Some particles will acquire enough energy to penetrate the wave, while others will remain trapped when the wave reaches point b in figure 1. When the wave reaches point c, the peak will have disappeared, so rapid acceleration will no longer take place. This mechanism will therefore rapidly lower the mirror points of trapped particles to the point at which peaks are no longer present on plots like figure 1.

The altitude at which this lowering ceases is illustrated in figure 2. Here $dB/ds$, where $B$ is the field strength and $s$ is a distance along a field line, is plotted for a dipole field line passing over the equator at 10 earth radii. This same quantity is shown for hydromagnetic waves with amplitudes of 1 to 300 gammas at 10 earth radii and rise times of 1 second. In this figure, it is assumed that the energy flux density remains constant as the wave propagates inwards, so the amplitude, $dB$, varies as $V_a^{-1/2}$ where $V_a$ is the Alfen velocity. Therefore, wave amplitudes at 6½ and 5 earth radii are about ½ and 1/3 the values indicated on figure 2 for 10 earth radii. It can be seen that if waves with amplitudes of about 10 gammas are present at 5 earth radii (the equivalent of 30 gammas at 10 earth radii), then trapped particles along this field line will have their mirror points lowered rapidly to about 5 earth radii.

Hydromagnetic disturbances can also result in a diffusion of charged particles across field lines (Parker, 1960; Herlofson, 1960). Whenever the magnetic moment is conserved, any diffusion of charged particles either along or across field lines will result in a change in the energy of the trapped
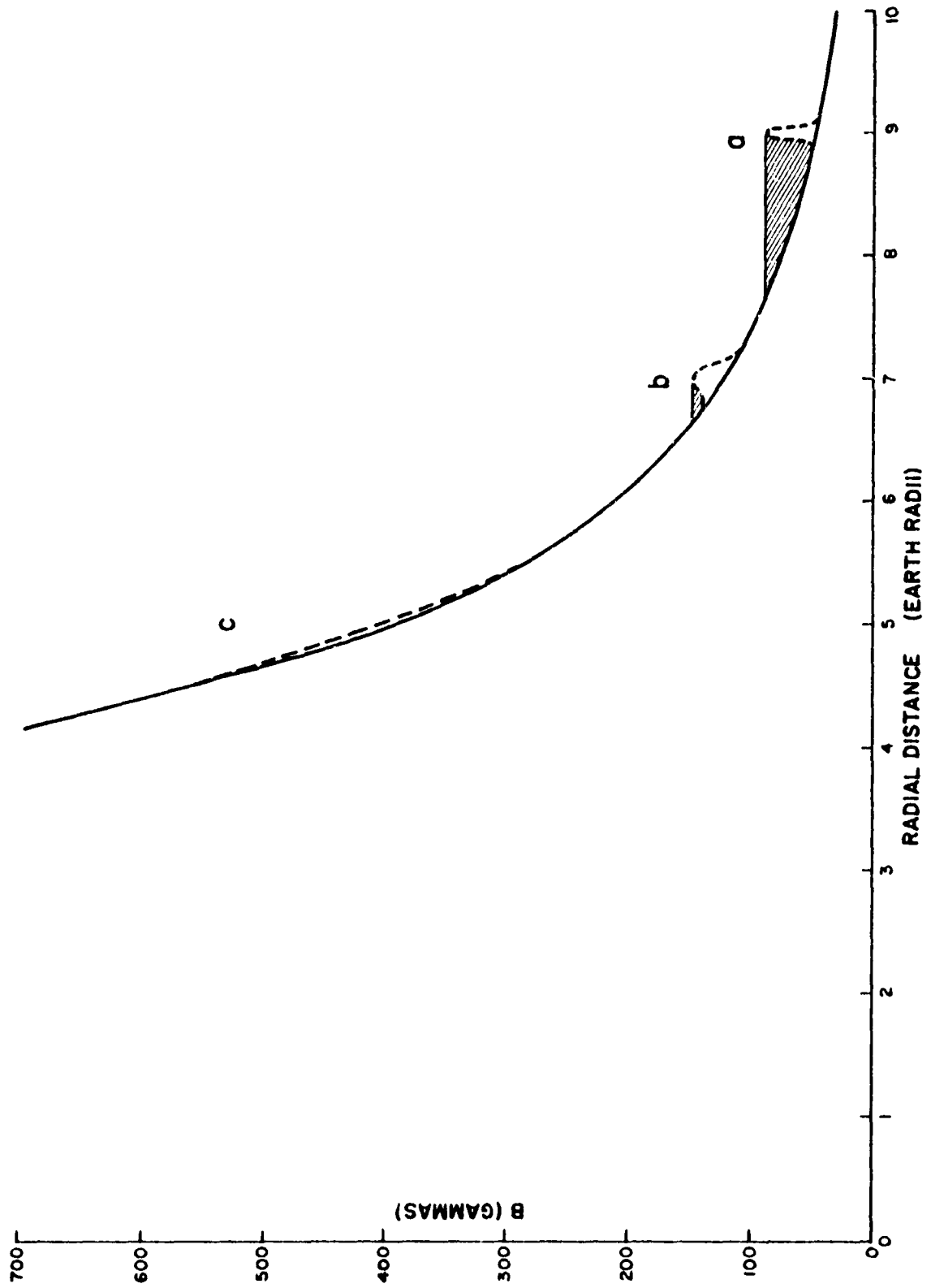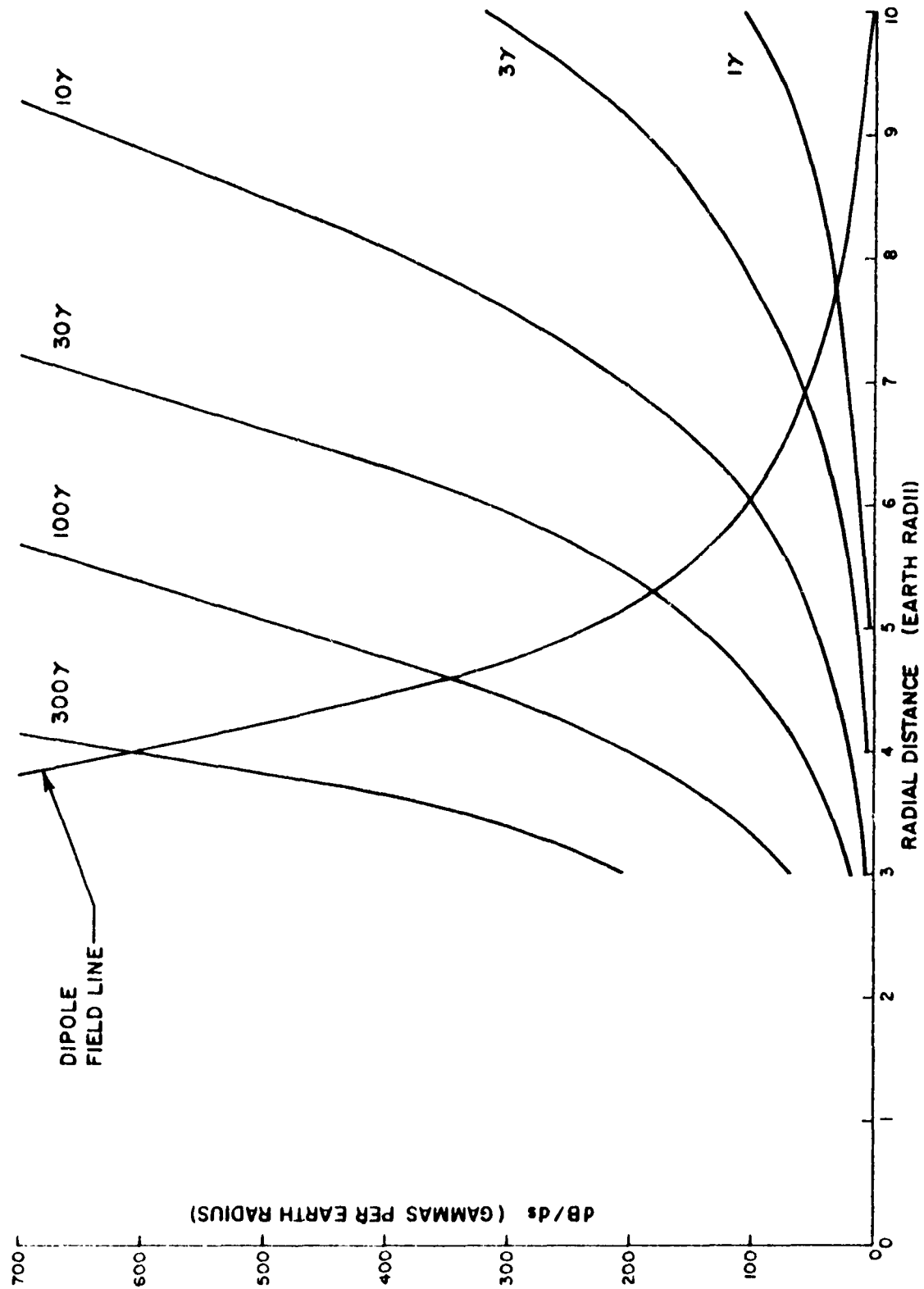
Figure 1. Propagation of a hydromagnetic wave.

Figure 2. Field gradients due to the earth's Dipole and hydromagnetic waves.

particles as discussed previously in connection with adiabatic invariants.

The measurements required to investigate the importance of Fermi acceleration throughout the magnetosphere involve a rather complete study of hydromagnetic waves including the shape, amplitude, and velocity of individual waves and the frequency spectrum of all waves which pass a given point in space. Wave velocities can be calculated if the magnetic field strength and plasma density are known.

Heating by hydromagnetic shock waves. It was seen in the last section that at altitudes below about 3 earth radii, protons may be accelerated because of interactions with low-frequency hydromagnetic waves. However, the extent of this acceleration is limited to about a factor of 10 to 100 since this mechanism increases the component of kinetic energy directed along a field line and, therefore, lowers the mirror point of the trapped particle into the atmosphere.

In regions in which the wave frequency approaches the proton-cyclotron frequency, scattering will take place so acceleration need not lower the mirror points as drastically. Dessler, Hanson, and Parker (1961) discussed the formation of hydromagnetic shock waves above the night side of the earth and showed that ambient protons can be rapidly accelerated to about the wave velocity, which can amount to an acceleration from thermal energies to 100 kilovolts at 1.5 to 2 earth radii, 1 kilovolt at 4 earth radii, and about 10 electron volts at 10 earth radii. This is really just another form of the Fermi mechanism as it involves the reflection of a trapped proton from the sharp crest of a hydromagnetic shock wave.

Since a large-scale acceleration of protons at low altitudes requires hydromagnetic waves with a high frequency component, the experimental measurement required is the frequency spectrum of hydromagnetic disturbances below about 4 earth radii in the range of 1 to 100 cps.

Betatron acceleration. If the magnetic field in which a charged particle is trapped undergoes a slow, uniform compression, the energy of the charged particle is increased. The fractional energy increase is a function of the speed and pitch angle of the trapped particle, but reaches a maximum value equal to the fractional increase in field strength when the particle is nonrelativistic

and when the particle mirrors at the magnetic equator. Both protons and
electrons can be accelerated by this mechanism, though it is slightly easier
to increase the energy of a proton than that of an electron at the same energy
because of the relativistic effect. At energies below 200 kilovolts, electron
acceleration by the betatron mechanism is at least half as efficient as proton
acceleration. The effect of this mechanism on trapped particles has been
discussed in more detail by Coleman (1961). He showed that for an isotropic
particle flux whose energy spectrum is initially given by

$$N( >E ) = kE^{-\gamma}$$

betatron deceleration results in a slight decrease in $\gamma$ (hardening). In the
above expression, $N ( > E )$ is the number of particles with energies greater
than E, and k and $\gamma$ are parameters. If $\gamma$ is initially 3.0, it will increase
to 3.1 if the field strength is increased to 1.6 times its initial value and it
will decrease to 2.9 if the field strength is decreased to 0.4 times its initial
value.

Dessler and Karplus (1961) have described the effects of betatron accelera-
tion produced by field changes accompanying the formation and disappear-
ance of a ring current. This provides a mechanism by which the energy
spectrum and flux of high-energy particles can be altered as a result of the
acceleration, deceleration, injection, or removal of a large number of low-
energy particles.

Gold (1959) suggested that since the magnetosphere is separated from the
conducting earth by an insulating layer (the atmosphere), portions of the mag-
netosphere may undergo convective motion. Axford and Hines (1961) have
elaborated on this model and have described a convection system which may
be set up in the magnetosphere, and which would carry particles downward
from the boundary region. These particles would be accelerated by the beta-
tron mechanism as they are carried into regions of higher field strength.

The importance of the betatron mechanism can be determined by measuring
variations in the magnetic field strength as a function of time and by measuring
any large-scale convective motions. From these measurements and the initial
energy spectrum of trapped particles, the energy spectrum that would result
from betatron acceleration alone can be calculated at any later time, so that

changes due to this mechanism can be separated from changes due to other mechanisms.

Neutral line mechanism. If an electric field is set up between two points in the magnetosphere, particles cannot in general flow rapidly to neutralize this field because the conductivity across field lines is relatively low. If a neutral line (a line along which the magnetic field strength is zero) were suddenly set up so that it connected these points, a discharge of particles could take place, and those particles would be accelerated by the electric field. If the neutral line is moving, an electric field of magnitude $\underset{\sim}{E} = \underset{\sim}{v} \times \underset{\sim}{B}/c$ can be set up because of the motion alone. This mechanism has been described by Dungey (1958). Akasofu and Chapman (1961) have proposed that neutral lines could be responsible for the rayed structure seen in auroras.

Neutral points or lines can be formed because of the mixing of the earth's field with the interplanetary field. It is also possible to form neutral points or lines on the surface of a cloud of solar plasma if it enters the magnetosphere, provided the cloud contains a magnetic field. The maximum path length for acceleration on a cloud's surface is equal to the cloud length, and the potential which could be set up depends on the cloud velocity and the field strength. For cloud dimensions on the order of 1,000 kilometers, field strengths of 30 $\gamma$ to 100 $\gamma$, and velocities of a few hundred kilometers per second, acceleration to an energy of tens of kilovolts is possible. Finally, neutral lines could be formed in the vicinity of a very strong ring current (Akasofu and Chapman, 1961). The most likely place in the magnetosphere for such a neutral line to form is over the night side of the earth.

When an x-type neutral line is formed, particles are accelerated along the line. To explain aurora production, Akasofu and Chapman (1961) noted that the magnetic moment of a particle is not conserved in the vicinity of a neutral line. Therefore, particles are spread within the thin sheet in which acceleration takes place, so that some will be traveling along field lines when they leave the acceleration region and will strike the dense atmosphere. Particles which are trapped along a field line passing through a neutral point will also be scattered because of the nonconservation of the magnetic moment in the vicinity of the neutral point. A neutral point can, therefore, also serve to remove trapped particles from a given region by scattering them into the dense atmosphere.

A magnetometer passing near a neutral point would detect a change in the direction of the field, though the field strength would not go to zero. However, the observation of such a change would not necessarily imply the presence of a neutral point. It is therefore necessary to observe the accelerated particles to determine if this mechanism is important. The energy range of interest for acceleration of background particles is 1 kev to 100 kev. Any particles trapped along a line of force passing through a neutral point can be scattered into the dense atmosphere, so that the flux of particles above the maximum energy to which acceleration is taking place would be reduced along these field lines. The detection of a region with such an energy spectrum would imply the presence of a neutral point or line.

Acceleration by electromagnetic radiation. Helliwell and Bell (1960) suggested that trapped particles could be accelerated by interactions with whistlers or other low frequency electromagnetic radiation in the magnetosphere. This mechanism involves the coupling of energy between an elliptically polarized wave traveling along a field line and a trapped particle whose cyclotron frequency is near the wave frequency. Parker (1961) has studied this mechanism in some detail and has concluded that if very strong whistlers are present, rapid synchronous acceleration of trapped electrons is possible, while whistlers with smaller amplitudes will produce a slower nonsynchronous or transresonant acceleration resulting from a random walk drift in electron velocity. A preliminary report of measurements made by Cain, Shapiro, Stolarik, and Heppner (1961) indicate that some whistlers are strong enough to produce rapid acceleration. However, since whistler amplitudes do not increase greatly with increasing solar activity, this mechanism cannot produce the large-scale changes in trapped particle fluxes that are observed during magnetic storms. The measurements required are a determination of the frequency spectrum of whistlers or other low-frequency electromagnetic disturbances in the magnetosphere.

Equilibration. It is certain that much of the trapped radiation is not at a Maxwell equilibrium, and that energetic trapped particles will transfer energy to the background plasma. The rate at which energy will be transferred can be determined from the equipartition times given by Spitzer (1956). Electrons with energies below about 10 kilovolts will transfer an appreciable fraction of

their energy to electrons in the background plasma. Electrons with energies above about 100 kilovolts will probably not lose much energy in this manner, since they are likely to be lost because of interactions with hydromagnetic waves. As an example of the importance of this source of heating, assume kilovolt electrons are present with a density of 1 per $cm^3$ (flux of $2 \times 10^9$ $cm^{-2} \cdot sec^{-1}$). If the background plasma density is $10^3$ electrons and ions per $cm^3$, about 250 ev $\cdot$ $cm^{-3} \cdot day^{-1}$ of energy is dissipated by this mechanism. An equal flux of 10-kilovolt electrons would dissipate about 40 ev $\cdot$ $cm^{-3} \cdot day^{-1}$. Moderate energy protons are a less important source of heating of the background electrons since they can be lost by charge exchange and scattering from hydromagnetic waves before dissipating much energy.

The importance of high-energy trapped particles in the heating of the background plasma depends on the particle lifetimes and on the charged particle density. The measurements required are a determination of the electron temperature and density, particularly in the outer Van Allen belt. These measurements will also aid in determining the lifetimes of trapped electrons.

Collisional acceleration. High-energy trapped particles can undergo ionizing collisions with hydrogen atoms in the magnetosphere, and the secondary electrons produced will then contribute to the flux of trapped radiation. Above the oxygen-nitrogen atmosphere, trapped electrons with energies below 10 or a few tens of kilovolts can transfer an appreciable fraction of their energy to secondary electrons, while protons will not do so. Most of the secondary electrons will have energies of less than a kilovolt, but a small fraction will have higher energies.

In the dense atmosphere, however, both protons and electrons will lose energy rapidly and will produce a large number of secondary electrons. Therefore, at altitudes of less than 1,500 km, secondary electrons can form an appreciable fraction of the electron flux (Kellogg, 1960). Because of the short lifetimes of electrons mirroring at these altitudes, however, these electrons will not supply an important contribution to electron fluxes observed at radial distances of more than 1.5 earth radii.

Summary. The mechanisms will be summarized by regrouping them according to the type and energy of the particle which can be accelerated:

a. Kilovolt protons can be produced in the boundary region by Fermi acceleration from moving turbulent structures or clouds. Protons with energies of a kilovolt and below can be produced at radial distance of 4 earth radii and above, because of heating by hydromagnetic shock waves.

b. Protons with energies of tens of kilovolts can be produced in the vicinity of neutral points or lines. Particles accelerated by this mechanism could be found in almost any part of the magnetosphere. The proton spectrum produced by Fermi acceleration has a high energy tail that extends to tens or hundreds of kilovolts. Protons could be accelerated to tens of kilovolts below 4 earth radii if high-frequency hydromagnetic waves or shocks are formed in this region.

c. Kilovolt electrons can be produced within the boundary region by acceleration in clouds or by the setting up of plasma oscillations. Electrons may also be temporarily accelerated to kilovolt energies near the interface at which the solar plasma is deflected. In regions in which a large flux of high energy protons or electrons is present, kilovolt energy secondary electrons will be produced by collisions of the high-energy trapped particles with ambient atoms. At altitudes of about 2,000 km and below, secondary electrons can form a large fraction of the electron flux.

d. Electrons can be accelerated to tens of kilovolts in the vicinity of neutral points or lines. If a large flux of kilovolt electrons is produced in the boundary region, their energies can be increased to tens or hundreds of kilovolts as a result of Fermi acceleration. Electromagnetic radiation is capable of accelerating electrons to tens of kilovolts. This process would take place rather slowly and would not cause a sudden change in fluxes during a magnetic storm.

e. Betatron acceleration could increase the energy of any trapped particle. The fractional energy increase, however, is limited by the fractional change in field strength. Betatron acceleration could be caused by an increase in the solar-wind pressure, by the motion of a group of particles in a convection system, or by a decrease in the intensity of a ring current. An increase in a ring current would decelerate trapped particles.

## 5. MEASUREMENTS REQUIRED TO INTERPRET TESTS OF ACCELERATION MECHANISMS.

_Measurement of ambient conditions._ Any interpretation of experimental results in terms of acceleration mechanisms will be unreliable unless the fluxes of ambient particles which are available to be accelerated is known. It is therefore important to obtain an accurate picture of the magnetosphere during quiet times, and to obtain measurements of the density and temperature of the background plasma during quiet and disturbed times.

_Particle lifetimes._ Even if it is determined that a given mechanism is producing energetic particles at a given rate, it is not possible to decide with certainty whether this mechanism is producing the observed flux of trapped particles or whether it is merely making an insignificant contribution to this flux unless the lifetimes of the trapped particles are known. The most important measurements that are required to determine lifetimes are measurements of the speed, direction of motion, and detailed shapes of hydromagnetic waves, and measurements of the density and temperature of the background plasma and the neutral atoms. Measurements near 2 earth radii and below are particularly important since in this region the characteristic times for a change in mirror points of trapped particles due to interactions with hydro-magnetic waves becomes long, and scattering from atmospheric atoms and ions becomes important in determining lifetimes.

_Asymmetry of the magnetic field._ Some acceleration mechanisms will be far more efficient on one side of the earth than on the other side. An idea of the extent of the Van Alien belts and of the boundary region is therefore required on both the night side of the earth and the day side. The form of the inner Van Allen belt is probably nearly the same on the two sides. There is some evidence to indicate distortion of the outer belt by the solar wind (Liemohn, 1960). The boundary region is certainly quite different on opposite sides of the earth.

In particular, it should be noted that when the longitudinal invariant is conserved, particles will reach lower altitudes and will mirror at smaller latitudes over the night side of the earth then over the day side. A thin sheet of particles will also broaden as it drifts around the earth, and any mechanism which could move the mirror points of these particles towards the equator

along a field line on the day side of the earth would cause the belt to drift inwards over the night side.

6. CONCLUSIONS.

The conclusions of this work will be summarized by comparing the observed trapped particle fluxes with the fluxes that could be produced by various acceleration mechanisms in each region of space. A set of experimental tests that could determine which mechanisms are most important in each region will then be outlined.

In the boundary region, it was seen that protons can be accelerated to energies of several hundred kilovolts, and electrons to energies on the order of a kilovolt. The most important measurements to be made in this region to detect the presence of these particles and to determine how they are produced are as follows:

a. A determination of the proton energy spectrum from 100 ev to 1 Mev, with primary emphasis on the region from 1 kev to 100 kev.

b. A determination of the spatial distribution of protons with energies from a few electron volts to a few kilovolts. This measurement will detect the presence of turbulence and should be correlated with a measurement of the vector magnetic field.

c. Magnetic field measurements with two magnetometers separated by a distance of several hundred kilometers. This measurement will determine the size, speed, and direction of motion of turbulent structures and hydromagnetic disturbances.

d. A determination of the electron energy spectrum from 10 ev to 10 kev. A crude measurement of the angular distribution will assist in determining which mechanism is most important in producing these particles.

e. A measurement of the amplitude of magnetic or electromagnetic disturbances in the frequency range of 10 kc to 1 mc to detect the presence of plasma oscillations.

Several mechanisms could produce the energetic electrons which have been detected in the outer Van Allen belt. The neutral-line mechanism may be responsible for the electrons in the rayed auroral forms, but is is not likely

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to be important in supplying the rather uniform flux of electrons with energies in the tens and hundreds of kilovolts which have been detected from the boundary region near ten earth radii down into the inner Van Allen belt.

Betatron acceleration due to an increase in the solar-wind pressure or a decrease in the intensity of a ring current could cause a large increase in the flux of electrons with energies above about 1 Mev. In this energy range, the spectrum is quite steep, so a small fractional change in the energies of all trapped particles would result in a large change in the flux observed above a given threshold. From 40 kev to 100 kev, however, the energy spectrum is rather flat (O'Brien, Van Allen, Laughlin, and Frank, 1962), and it does not appear possible to account for the observed 10- to 20-fold variations in the electron flux throughout this energy range in terms of betatron acceleration alone.

It is more likely that Fermi acceleration within the magnetosphere, possibly coupled with betatron acceleration caused by large-scale convection within the magnetosphere, is responsible for the production of energetic electrons in the outer Van Allen belt. Lifetimes of 100-kilovolt electrons in the outer belt due to Fermi acceleration during quiet times have been estimated (Parker, 1961a) to be a few months, and at high altitudes the characteristic times are much shorter. Since these characteristic times are inversely proportional to the square of the hydromagnetic wave amplitude, it is possible that during magnetic storms, lifetimes could be reduced to the order of a day. Therefore, mechanisms are available for producing kilovolt electrons in the boundary region and mechanisms are available for accelerating these electrons along field lines to energies on the order of 100 kev. It is also possible that this acceleration could take place in about a day, so that it could produce a large change in the flux of trapped particles during a single magnetic storm.

Any of several mechanisms could carry these energetic particles from the boundary region down to the heart of the outer Van Allen belt near 4 earth radii. The large-scale convection system mentioned previously could carry kilovolt energy particles quite efficiently. Higher energy (100 kev) particles would tend to drift out of the convection system, and would alternately be moved inwards and outwards on successive passes through the convection system. They could still experience a fairly rapid net inwards drift because of repeated interactions with the convection system.

It is also possible that the boundary region is compressed down to about 4 earth radii during magnetic storms, or that large-scale intrusions are formed which extend down to low altitudes. These mechanisms would produce energetic particles directly in the outer Van Allen belt.

Finally, a breakdown of the third adiabatic invariant during magnetic storms can result in a motion of trapped particles across field lines (Parker, 1960). This mechanism does not appear to be fast enough to carry particles from the boundary region near 8 or 10 earth radii down to 4 earth radii during a single storm, but it may be quite important in determining the distribution of particles in the relatively stable portions of the magnetosphere (such as the inner portion of the outer Van Allen belt).

The changes in trapped particle fluxes during a storm can now be investigated. During quiet times, electrons would be accelerated in the boundary region, and the observed flux in the outer belt could either represent an equilibrium with electrons being continuously injected by a convection system and removed by the convection system and other loss mechanisms, or the observed flux could simply be decaying slowly, with a characteristic time of several months.

The onset of a magnetic storm would be accompanied by increased hydromagnetic-wave activity. Initially electrons in the boundary region would be accelerated in greater numbers and to higher energies than during quiet times, and the lifetimes of electrons throughout the magnetosphere would decrease. The first detectable result in the outer belt would therefore be an increase in the loss rate with no increase in the rate of injection. After some period of time the injection rate would increase as new particles are carried down by the convection system, as the interface is compressed, or as large scale intrusions form. This would, then, produce an increase in the flux to above the quiet-time value.

The measurements required in this region from the interface down into the outer belt are therefore:

a. Observation of the spatial distribution of electrons with energies between 100 ev and 100 kev. These measurements would detect the presence of intrusions or a convection system carrying kilovolt electrons, and by

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measuring the time required for these electrons to reach a given altitude after the onset of a magnetic storm, could measure the velocity of such a system.

b. A convection system not carrying kilovolt electrons would at least carry protons with energies between 10 ev and several kilovolts, so could be detected with a low energy proton analyzer and magnetometer combination similar to that which would be used to detect turbulence and Fermi acceleration in the boundary region. If turbulent structures are carried along with the convection system, their velocity would be measured with a two magnetometer experiment like the one described previously.

The details of dumping during a storm can be studied by measuring the mirror-point distribution of electrons in the energy range of 1 kev to 1 Mev, and by investigating the frequency spectrum of hydromagnetic waves. It is particularly important to measure the wave spectrum below two earth radii since the characteristic time for mirror-point lowering due to interactions with hydromagnetic waves becomes long at low altitudes, and other processes such as atmospheric scattering become important. Therefore, actual lifetimes may depend very sensitively on the hydromagnetic wave spectrum at low altitudes.

The mirror-point distribution can be obtained from the count rate of an omnidirectional counter that either follows along a field line or cuts the line at a number of points. A collimated counter with an infinitely small angular aperture could determine the entire mirror-point distribution by traveling radially outward in the equatorial plane, but if the pitch angle is only known to an accuracy of $\Delta\theta$ (a combined error due to uncertainties in the field direction and due to the angular resolution of the particle detector), then the error in the mirror point field strength can be found by differentiation of the equation $\frac{B}{B_m} = \sin^2 \theta$, giving $\frac{\Delta B_m}{B_m} = \frac{-2\Delta\theta}{\sin\theta}$. In these expressions, B is the field strength at the detector and $B_m$ is the field strength at the particle's mirror point. If $\Delta\theta$ equals five degrees and it is desired to limit the error in $B_m$ to 50 percent, then mirror-point densities can be determined only to a point where the field strength is eight times that at the observation point. An interpretation of the count rate of an experimental instrument in terms of

mirror-point densities requires a knowledge of the energy spectrum of the particles detected. It is therefore preferable to detect particles in a few narrow energy channels spread throughout the region of interest than to cover the whole region in an equal number of broad channels.

If trapped particles are lost by acceleration along the field lines due to interactions with hydromagnetic waves, a general lowering of mirror points into the dense atmosphere should be observed. The rate of lowering would depend on the energy of the trapped particles and on the hydromagnetic-wave frequency spectrum. If expansion of the atmosphere is important, the altitude at which the density of trapped particles drops off rapidly would increase during the storm. If betatron acceleration and deceleration due to a ring current are important, the change in the energy spectrum and the displacement of the belts should agree with the calculation of Dessler and Karplus (1961).

Recently, several reports have been presented dealing with experimental observations of changes in the flux of protons trapped below four earth radii (Pizzella, McIlwain, and Van Allen, 1962; Davis, 1962). Of the mechanisms proposed to date, the only ones which can greatly increase the flux of protons in this region during a single storm are direct injections and interactions with hydromagnetic waves. Betatron acceleration due to the disappearance of a ring current could alter the high-energy component of the proton flux significantly, since the energy spectrum is quite steep here. It does not appear possible to produce a very large flux of protons with energies between 100 kev and 4.5 Mev by betatron acceleration alone, however, since the spectrum is not very steep at the lower end of this range (Davis, 1962).

Two types of interactions with hydromagnetic waves were discussed. First, low frequency waves can accelerate protons by the Fermi mechanism. As was mentioned previously, however, particles on low-latitude field lines can be accelerated by only about a factor of 10 to 100 in energy before they are lost in the atmosphere, so a source of moderate energy protons is still required. The only mechanism which has been proposed to accelerate protons from thermal energy to energies in excess of a kilovolt is the interaction with high-frequency magnetic disturbances of hydromagnetic shock waves. Since the hydromagnetic wave velocity increases with decreasing radial distance (except at very low altitudes), shocks will not form as waves propagate from a point

on the boundary down to the earth. Therefore, the existence of high-frequency hydromagnetic waves or shocks at radial distances of less than 4 earth radii would imply the penetration of solar plasma down to about 4 earth radii or below. This penetration could be due to the compression of the interface to 4 earth radii or below, to the formation of intrusions which reach down to these altitudes, or to the extension of a convection system which carries turbulent structures down to these altitudes.

Hydromagnetic shock waves could accelerate protons to the local Alfén velocity, and Fermi acceleration could increase this energy by a factor of 10 to 100 on low field lines. A combination of these mechanisms could, therefore, produce protons with energies as high as several Mev below about 2 to 3 earth radii. It does not appear possible, however, to accelerate protons to even 100 kev at altitudes of 4 earth radii or above (the Alfen velocity at 4 earth radii is about equal to the velocity of a 1-kev proton). Since protons with energies in excess of 100 kev are observed well beyond 4 earth radii, some other mechanism is required.

It was noted previously that protons with energies extending up to tens or hundreds of kilovolts can be produced in the boundary region. The most probable explanations for the presence of protons with energies between 100 kev and several Mev within the magnetosphere are that the protons are either first accelerated in the boundary region and carried inwards (and further accelerated as they move to regions of higher field strength) by a convection system or as the interface is compressed, or they are solar protons which are carried inwards by these mechanisms.

No acceleration mechanisms have been proposed which could accelerate trapped protons from thermal energies to energies on the order of 100 Mev. This leaves the neutron albedo mechanism and direct injection as the remaining possibilities. It is possible, however, for the betatron or the Fermi mechanism to increase the energy of these energetic protons by about a factor of 10 to 100 on low field lines before they are lost in the atmosphere.

Measurements required in the region from 1.2 to 4 earth radii and generally over the equator are:

　a.　Measurements of hydromagnetic fluctuations to frequencies of 100 cps.

b. Measurements of the proton spectrum from 1 kev to several Mev. If a convection system brings these protons down below 4 earth radii, the flux of protons with energies near 1 kev would increase first after the onset of a magnetic storm, while protons with energies in excess of 100 kev would increase more slowly due to the decreased speed of convection at high energies.

c. The proton spectrum from several Mev to 1,000 Mev should be analyzed along with magnetic-field measurements to determine if betatron or Fermi acceleration appreciably alters the energy of these protons.

APPENDIX

Vehicle Potential

At low altitudes, a vehicle becomes negatively charged to a few volts or less since a neutral vehicle will make more collisions with the fast electrons than with the slower ions (Chopra, 1961). At higher altitudes, this effect becomes less important because the plasma density is small, and here photoelectrons emitted from the vehicle become important. For the cases of a 25-ev plasma and a 1-ev plasma with densities of $10^2$ cm$^{-3}$, a slow neutral vehicle will encounter an excess of about $3 \times 10^{10}$ and $7 \times 10^9$ electrons $\cdot$ cm$^{-2}$ $\cdot$ sec$^{-1}$. The following indicate the fluxes of photons arriving in the vicinity of the earth with their energies:

$$> 6 \text{ ev} \approx 3 \times 10^{13} \text{ cm}^{-2}/\text{sec}^{-1}$$

$$> 8 \text{ ev} \approx 1 \times 10^{12} \text{ cm}^{-2}/\text{sec}^{-1}$$

$$> 10 \text{ ev} \approx 4 \times 10^{11} \text{ cm}^{-2}/\text{sec}^{-2}$$

$$> 12 \text{ ev} \approx 5 \times 10^{10} \text{ cm}^{-2}/\text{sec}^{-2}$$

$$> 30 \text{ ev} \approx 2 \times 10^{10} \text{ cm}^{-2}/\text{sec}^{-2}$$

$$> 100 \text{ ev} \approx 2 \times 10^9 \text{ cm}^{-2}/\text{sec}^{-2}$$

(Hinteregger, 1961)

The photoelectric yield is on the order of 10 percent above 12 ev for most metals and drops to 1 percent at 10 ev, at least for the metals (with relatively large work functions) which were studied by Walker, Wainfan, and Weissler (1955). The photoelectric yield could remain above 1 percent at photon energies as low as 6 to 8 ev for some metals with small work functions. The energy spectrum of photoelectrons produced by photons with energies above 20 or 30 ev contains relatively few electrons with energies near that of the incident photon, but is rich in low energy electrons. Therefore, the vehicle potential will depend sensitively on the actual plasma density. If a 1 ev plasma is present, the potential could be negative by one or a few volts if the plasma density is slightly higher than $10^2$ per cm$^3$, but the potential is more likely to be positive by less than twenty volts. If a 25 ev plasma is

present, the potential could be anywhere from minus a few tens of volts to plus ten or twenty volts. In a turbulent region the density may vary appreciably in time intervals of a few seconds to a few minutes, so the vehicle potential could change by tens of volts during such intervals. The density of the streaming solar wind is about ten protons and electrons per $cm^3$, which would result in a positive potential of less than about twenty volts beyond the boundary region unless the plasma temperature is much higher than presently estimated.

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| 1 | Chief, Division of Technical Information Extension, US Atomic Energy Commission, Box 62, Oak Ridge, Tenn |
| 1 | Director, University of California Lawrence Radiation Laboratory (Technical Information Division), P. O. Box 808, Livermore, Calif |
| 1 | University of California Lawrence Radiation Laboratory, (Technical Information Division), Berkeley, Calif |
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| 1 | Director, National Bureau of Standards, Central Radio Propagation Laboratory, Boulder, Colo |
| 1 | Space Technology Labs, Inc., (Information Center, Document Procurement), P. O. Box 95001, Los Angeles 45, Calif |
| 1 | Battelle Memorial Institute, 505 King Avenue, Columbus, Ohio |
| 1 | Official Record Copy, (SWRPT, Lt Kaufmann) |

Air Force Special Weapons Center, Kirtland AF Base, New Mexico
Rpt. No. AFSWC-TDR-62-133. EXPERIMENTAL TESTS FOR THE ACCELERATION OF TRAPPED PARTICLES.
Jan 63, incl illus., table, 37 refs, 41 p.
Unclassified Report

Mechanisms which could result in the acceleration of charged particles within the magnetosphere are discussed in terms of the responses expected from experimental instruments as they pass through acceleration regions. A series of experimental tests is outlined which can determine if acceleration of trapped particles is important. The mechanisms discussed include Fermi acceleration, which can accelerate protons to tens or hundreds of kilovolts and can increase the energy of trapped electrons several hundred-fold before they are lost in the dense atmosphere. A change

1. Acceleration
2. Albedo
3. Cosmic protons
4. Cosmic radiation
5. Electrons
6. Elementary particles
7. Magnetic fields
8. Neutron reactions
9. Plasma
10. Radiation belts
I. AFSC Project 78..
Task 78.107
II. Richard L. Kaufmann, 1/Lt, USAF
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